Radiation Protection Dosimetry Vol. 105, No. 1–4, pp. 601–608 (2003)
Published by Nuclear Technology Publishing
© 2003 Nuclear Technology Publishing

UNCERTAINTIES IN THYROID DOSE RECONSTRUCTION AFTER CHERNOBYL

I. Likhtarev†, V. Minenko‡, V. Khrouch§ and A. Bouville‖
†Radiation Protection Institute, Ukrainian Academy of Technological Sciences,
Melnikova 53, 04050 Kiev, Ukraine
‡Research Clinical Institute of Radiation Medicine and Endocrinology
Minsk, Belarus
§State Research Center — Institute of Biophysics, Zhivopisnaja 46
Moscow 123182, Russian Federation
‖National Cancer Institute, DHHS, NIH
Division of Cancer Epidemiology and Genetics
EPS 7094, Bethesda, MD 20892, USA

INVITED PAPER

Abstract — The most significant impact of the Chernobyl accident of 26 April 1986 is the increased incidence of thyroid cancer among Belarusians, Russians and Ukrainians who were exposed as children to radioiodines in fallout resulting from atmospheric releases. The US National Cancer Institute (NCI), in cooperation with the ministries of health of Belarus and Ukraine, is involved in epidemiological studies of thyroid diseases related to the accident. Individual thyroid doses, as well as uncertainties, have been estimated for the members of the cohort studies (approximately 13,000 Ukrainians and 12,000 Belarusians). The cohort subjects, who were selected from the large group of children whose thyroids were monitored for gamma radiation within a few weeks of the accident, provided personal information on their residence history and dietary habits during interviews. Thyroid dose estimates range from 1 mGy to more than 20 Gy. The uncertainties are found to be approximately log–normally distributed, with geometric standard deviations ranging from 1.6 to 5.0. The medians of the geometric standard deviations are 1.7 for the Ukrainian subjects and 2.1 for the Belarusian subjects. The major sources of uncertainty in the thyroid dose estimates are found to be those related to the thyroid mass of the subject and to the estimation of the thyroidal content of ^{131}I at the time of thyroid monitoring.

INTRODUCTION

The accident of 26 April 1986 at the Chernobyl nuclear power plant, located in Ukraine about 12 km south of the border with Belarus, was the most serious ever to have occurred in the nuclear industry. Massive releases of radioactive materials into the atmosphere led to substantial radiation exposures among the populations of Ukraine, Belarus and Russia. These radiation exposures were due initially to ^{131}I and short-lived radionuclides and subsequently to radiocaesiums (^{134}Cs and ^{137}Cs) from both external irradiation and the consumption of foods contaminated with these radionuclides[1].

Beginning four years after the accident, an increase in the number of thyroid cancers was observed among children, both in Belarus and in Ukraine[2,3], where thyroid doses among children had been estimated to be relatively high[4,5]. In the mid-1990s, the US National Cancer Institute (NCI) conducted a case–control study in Belarus which concluded that there is a relationship between thyroid dose and cancer in the heavily contaminated areas of Belarus[6,7]. There is now little doubt that the increase in the incidence of thyroid cancer is to some extent related to radiation exposures resulting from the Chernobyl accident[1,8]. The exact nature of the relationship between thyroid dose and thyroid cancer, however, remains to be quantified.

Information on thyroid doses received by the populations living in contaminated areas is summarised in the 2000 report of UNSCEAR[1]. The most important contribution to the thyroid dose was due to the intake of ^{131}I, which occurred mainly via the consumption of contaminated cows' milk and milk products, with minor contributions arising from inhalation and the consumption of leafy vegetables. For some persons, consumption of goats' milk was an important source of radioiodine intake. Because the half-life of ^{131}I is only 8.04 days, most of the dose was delivered within a few weeks of the accident. Other, usually minor, contributions to the thyroid dose result from the intake of short-lived radioiodines (^{133}I and ^{135}I) and radiotelluriums (^{131m}Te and ^{132}Te), from the intake of the long-lived radiocaesiums (^{134}Cs and ^{137}Cs), and from external irradiation arising from the deposition of radionuclides on the ground[9].

In recent years, epidemiological studies investigating the relationship between the ^{131}I thyroid dose and thyroid cancer have been undertaken in all three

Contact author E-mail: Likh@rpi.kiev.ua

republics[10–12]. In these studies, individual thyroid doses, as well as uncertainties, need to be estimated for all subjects.

NCI entered into official binational agreements with the ministries of health of Belarus and Ukraine to pursue long-term cohort studies of thyroid diseases among the exposed populations[10]. The studies are outlined in similar research protocols, and designed to provide dose-specific estimates of the risk of thyroid diseases following childhood exposure to ^{131}I. All cohort subjects — approximately 13,000 in Ukraine and 12,000 in Belarus — were sampled among the large number of children who had their thyroids monitored for gamma radiation within a few weeks of the accident. This measurement led to the determination of the thyroidal content of ^{131}I at the time of the measurement. The thyroid dose due to ^{131}I intake was then derived from the thyroidal content of ^{131}I at that point in time, using personal information on residence history and dietary habits obtained during interviews, and models simulating the behaviour of ^{131}I in the environment and in the body. Uncertainties were estimated by means of Monte Carlo calculations, taking into consideration the uncertainties on most variables and parameter values that are used in the thyroid dose calculation. In order to ensure that the thyroid dose estimates and their uncertainties were comparable for the Ukrainian and Belarusian subjects, a joint methodology of calculation of the thyroid doses and of their uncertainties was developed by the dosimetrists from Belarus, Ukraine, Russia and the US who are involved in the studies.

In a separate assessment, thyroid doses are calculated using only the results of personal interviews, combined with models simulating the behaviour of ^{131}I in the environment and in the body. Large uncertainties are associated with the dose estimates calculated by this method, because it is not anchored on a thyroid measurement for each individual. This method is, however, useful as it allows a judgement of the reliability of the responses to personal interviews to be made. In addition, this type of method is the only one that can be applied in case–control studies, such as those conducted in Russia by the International Consortium for Research on the Health Effects of Radiation[11] and in Belarus and in Russia by the International Agency for Research on Cancer[12]. In this type of method, the most important sources of uncertainty are usually the ^{131}I deposition density, the interception coefficient by pasture grass, the transfer coefficient from pasture intake to cows' milk for ^{131}I, the milk consumption rate, and the thyroid mass. Results obtained when thyroid measurements are either absent or ignored also are presented and discussed.

Most of the accomplishments in dosimetric efforts so far have been related to the assessment of individual thyroid doses from ^{131}I. Thyroid doses resulting from external irradiation and from intakes of radionuclides other than ^{131}I are not discussed in this paper.

METHODOLOGY OF THYROID DOSE ESTIMATION

In Belarus as well as in Ukraine, the assessment of the thyroid doses from internal irradiation is based on the results of measurements of external gamma radiation by means of radiation detectors placed against the neck. Within a few weeks of the accident, approximately 200,000 of those measurements (called 'direct thyroid measurements') were made in Belarus and 150,000 in Ukraine. All cohort subjects — approximately 13,000 in Ukraine and 12,000 in Belarus — were sampled among the large number of children who were 0 to 18 y old at the time of the accident, with direct thyroid measurements.

Usually individuals were measured only once, so that only the thyroid dose rate at the time of measurement can be readily derived from the measurement. To calculate the thyroid dose, the variation with time of the thyroid dose rate had to be assessed. This was done using an ecological model, which determines the relative rate of intake of ^{131}I, both before and after the measurement, and takes into account the metabolism of ^{131}I in the body which may have been modified by the intake of stable iodine for prophylactic purposes. Personal interviews were conducted in order to obtain information on residence history, dietary habits and individual actions taken to reduce doses. Figure 1 shows the data and the procedures used to estimate the individual thyroid doses. Some of those procedures are discussed below.

Direct thyroid measurement

The direct thyroid measurement consisted of placing a gamma radiation detector against the neck. The position of the detector favoured the detection of gamma rays arising from the radioactive decay of ^{131}I in the thyroid; as the measurements were made, in most cases, at least several days after the accident, the contribution of short-lived radioiodines to the detector response was usually insignificant. Background consisted of gamma rays due to: (1) radioactive isotopes of caesium (^{134}Cs, ^{136}Cs and ^{137}Cs), which were distributed relatively uniformly throughout the entire body, (2) radionuclides deposited on the hair, skin and clothes of the individual being measured, in cases where appropriate measures had not been taken, (3) radionuclides deposited on the ground and in the room where the measurement was made, and (4) naturally occurring radiation. The indication of the detector was either in terms of exposure rate (μR h^{-1} or mR h^{-1}) or, for energy selective devices used in Ukraine, in counts per minute from an energy window centred on the 364 keV peak of ^{131}I. Background was subtracted from the direct thyroid measurement, usually on the basis of another measurement, sometimes made against the shoulder, the liver or the thigh of the individual, or, more often, in the absence of the individual. In Belarus, the direct thyroid measurements were often made by inexperienced people using a variety of devices that were not collimated, whereas in Ukraine the direct thyroid measurements were made by experienced people using collimated instruments, so that the results of measurements made in Ukraine can be considered to be much more reliable.

The ^{131}I activity present in the thyroid at the time of measurement, t_M, was derived from the net exposure rate using the calibration coefficient for the detector. Depending on how the direct thyroid measurement and the background measurement were conducted, the net exposure or count rate had to be corrected to account for the gamma radiation due to the radiocaesium activity in the body and/or to the contamination of clothes, hair or skin.

The calibration coefficient provides the correspondence between the reading recorded by the device and the ^{131}I activity present in the thyroid at the time of measurement. The value of the calibration coefficient depends on the device that was used, the geometry of measurement and the size of the thyroid. In Belarus, the determination of the calibration coefficient was based on measurements made on volunteers at the Moscow Institute of Biophysics as well as on an ongoing series of Monte Carlo calculations(13). In Ukraine, the values of the calibration coefficients were practically always recorded properly. In addition, careful measurements and detailed calculations were carried out in order to estimate the uncertainties attached to the estimated values of the calibration coefficients(14). These uncertainties are mainly due to three factors:

(1) The statistical counting error, which was greater as the ^{131}I content in the thyroid was lower. Because of the short half-life of ^{131}I, the ^{131}I content in the thyroid was usually relatively low when the measurement was made more than 1 month after the accident.
(2) Errors in the estimation of the background, which are especially important when the measurement device was not energy selective.
(3) Differences between the standard geometric conditions in which the calibration coefficient was determined and the real conditions of measurement of the cohort subjects in the field (position of the detector, thyroid size, thickness of tissue between the thyroid and the detector, etc.).

Ecological model

As shown in Figure 1, the ecological model (compartment 7) uses as input the contents of databases on ^{131}I ground deposition (compartment 4) and on ^{137}Cs ground deposition (compartment 3), takes into account the set of parameters that characterise the human exposure pathways leading to inhalation and to the consumption of cows' milk and leafy vegetables (compartment 5), and takes into consideration information on residence history, dietary habits and iodine prophylaxis obtained during personal interviews of the cohort subjects (compartment 2).

The ecological model, which does not make use of

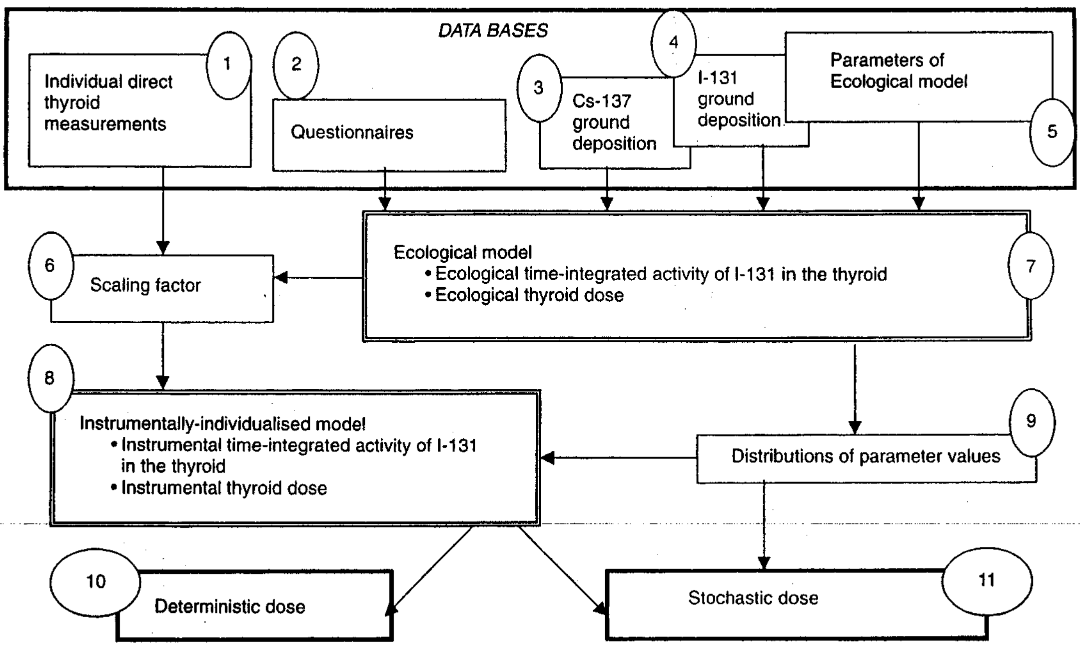

Figure 1. Data and procedures used to estimate the individual thyroid dose.

the information related to the direct thyroid measurements, has the following endpoints:

(1) A calculated thyroidal content of ^{131}I at the time of measurement that corresponds to the ecological model and its parameter values.
(2) A calculated time-integrated activity of ^{131}I in the thyroid.
(3) A corresponding individual 'ecological' (or 'model') thyroid dose.

Scaling factor

The calculated thyroidal content of ^{131}I at the time of measurement obtained for each cohort member was compared with the result of the direct thyroid measurement (compartment 1 in Figure 1). The ratio of the two values is the scaling factor, which was calculated for all cohort subjects (compartment 6 in Figure 1).

Estimation of the deterministic doses

The values of the time-integrated activity of ^{131}I in the thyroid and of the thyroid dose (compartment 7 in Figure 1) were calculated for each cohort member with the ecological model. Then those values were corrected with the individual scaling factor (compartment 6 in Figure 1). These procedures resulted in the determination of a set of instrumental-individual activities and of thyroid doses (compartment 8 in Figure 1).

This set of doses may be defined as deterministic individual doses (compartment 10 in Figure 1), as it is based on the 'central' estimates of the parameter of the ecological model.

Estimation of the stochastic doses

Stochastic distributions of instrumental-individualised doses for every cohort member (compartment 11 in Figure 1) were calculated with a Monte Carlo type procedure. For that purpose, probability distributions were assigned to most of the main parameter values that were deemed to have a substantial influence on the thyroid dose estimate. Those parameters can be classified into five categories, namely those related to: (1) the derivation of the ^{131}I thyroidal content at the time of the direct thyroid measurement; (2) the transfer of ^{131}I in the environment; (3) the answers provided during the personal interviews; (4) the reduction in the ^{131}I concentrations in foodstuffs between production and consumption and (5) the transfer of ^{131}I in human bodies. The distributions of some of the parameters that were considered are shown in Table 1. It was assumed in the Monte Carlo calculations that all parameters were independent.

RESULTS AND DISCUSSION

Individual thyroid doses were estimated for the

Table 1. Best estimates and distributions of some of the parameter values.

Parameter			Best estimate	Distribution	
Description	Symbol	Unit		Type	Parameters*
Daily deposition of ^{137}Cs or ^{131}I	$P(t,s)$	kBq m^{-2} d^{-1}	Measured, interpolated, or calculated	Log–normal	GSD = 2.1 (BY) GSD = 1.6–2 (UA)
Interception coefficient	B_1	Unitless	Region dependent: 0.21, 0.36, 0.5	Triangular	0.13 –0.29, 0.22–0.5, 0.3–0.7
Transfer coefficient to cows' milk	f_m	d l^{-1}	4×10^{-3}	Log–normal	GSD = 2.1
Daily intake of grass by cow	I_p	kg d^{-1}	40	Uniform	30–50
Consumption rate of private cows' milk	R_3	l d^{-1}	Age- and country-dependent	Log–normal	GSD = 1.4–2.2 (BY) GSD = 1.4–2.6 (UA)
Removal rate from thyroid	λ_{th}	d^{-1}	Age-dependent	Normal	CV = 5%
Measured activity in thyroid	M_{res}	kBq	Device-dependent, age-dependent, etc.	Log–normal	GSD = 1.4–2.3 (BY) GSD = 1.1–1.4 (UA)
Thyroid mass	m_{th}	g	Age-dependent	Log–normal	GSD = 1.6

*GSD = geometric standard deviation; BY = Belarus; UA = Ukraine; CV = coefficient of variation.

approximately 13,000 Ukrainians and 12,000 Belarusians who are members of the cohorts considered in the epidemiological studies conducted by the ministries of health of Belarus and of Ukraine, in cooperation with NCI. All subjects were 0 to 18 y old at the time of the accident, had a direct thyroid measurement within a few weeks of the accident, and were interviewed to obtain information on their residence histories and dietary habits. Most of the subjects resided less than 200 km away from the reactor, on either side of the Ukrainian–Belarusian border, at the time of the accident.

Main properties of the deterministic and stochastic doses

The distributions of the Ukrainian and Belarusian subjects according to the geometric means of their thyroid dose are presented in Table 2. The analysis of the individual dose distributions showed that:

(1) The distribution shape is left asymmetric and very close to log–normal.
(2) The asymmetry is in general not very high: ratios between arithmetic and geometric means range from 1.11 to 1.30 for 94% of the dose estimates (Ukrainian cohort).
(3) The deterministic values of the thyroid doses are usually very close to the geometric means of the stochastic distributions.

The distributions of the uncertainties in the thyroid dose estimates, expressed as geometric standard deviations (GSDs) are shown in Figures 2 and 3 for the Belarusian and the Ukrainian subjects, respectively. The GSDs associated with these distributions vary from one individual to another and range from 1.6 to more than 5.0. The medians of the GSDs are 1.7 for the Ukrainian subjects and 2.1 for the Belarusian subjects. The results of a sensitivity analysis of the contributions of the various parameters to the uncertainty for a typical subject are shown in Figure 4. The parameters that account for most of the uncertainty are the thyroid mass and those related to the determination of the content of ^{131}I in the thyroid at the time of the direct thyroid measurement.

Because the uncertainties in the direct thyroid measurements are higher for Belarusians than for Ukrainians, the uncertainties in the thyroid dose estimates are, on average, higher for the Belarusian subjects than for the Ukrainian subjects.

Table 2. Distribution of the Ukrainian and Belarusian cohort subjects according to the geometric mean of their thyroid doses.

Thyroid dose interval (Gy)	Number of subjects	
	Ukraine	Belarus
0–0.3	7589	5039
0.31–1	3404	3438
>1	2227	3273
All	13,220	11,750

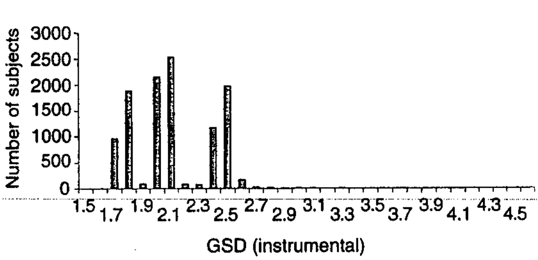

Figure 2. Distribution of the geometric standard deviation (GSD) of the thyroid dose for the Belarusian cohort subjects (instrumental model).

Scaling factor as a measure of ecological dose uncertainty

The average values of the scaling factor are close to unity for both Belarusian and Ukrainian cohorts (Figures 5 and 6). This shows that the estimates of the ^{131}I content of the thyroid at the time of the direct thyroid measurement that are calculated with the ecological model are, on average, in good agreement with estimates derived from the measurements. However, as can be seen in Figures 5 and 6, values of the scaling factor are greater than 10 for a substantial number of cohort subjects. These high values for the scaling factor are, as a rule, obtained for cohort subjects for which the ^{131}I signal from the direct thyroid measurement is close to, or indistinguishable from, background, resulting in high uncertainties in the estimate of the ^{131}I content in the thyroid. On the other hand, values for the scaling factor much lower than 1 are usually obtained when individuals respond that they did not consume any contaminated foodstuffs while the exposure rate from the thyroid is substantial.

The scaling factor range width is caused by uncer-

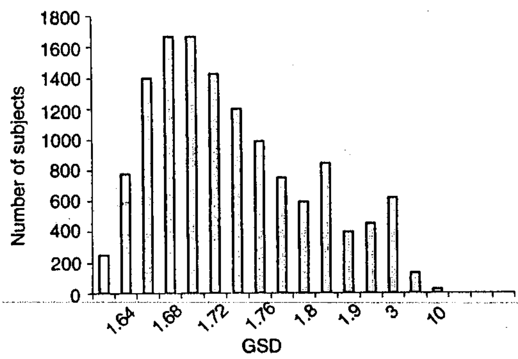

Figure 3. Distribution of the geometric standard deviation (GSD) of the thyroid dose for the Ukrainian cohort subjects (instrumental model).

tainty of dose assessments that in turn is produced by uncertainties of ecological model parameters and behavioural models of cohort subjects. This means that further steps are necessary to improve both the ecological model and the distribution of parameters in such a way that the cohort average of individual scaling factors will remain close to unity and that the range of individual scaling factors is substantially reduced.

The GSDs related to the thyroid dose estimates obtained by means of the ecological model for approximately 600 Belarusian subjects are presented in Figure 7. The median of the GSDs for these subjects is about 2.4. Therefore, as expected, the uncertainties in the thyroid dose estimates that are obtained by means of the ecological model are substantially greater than those obtained with the instrumental model. The results of a

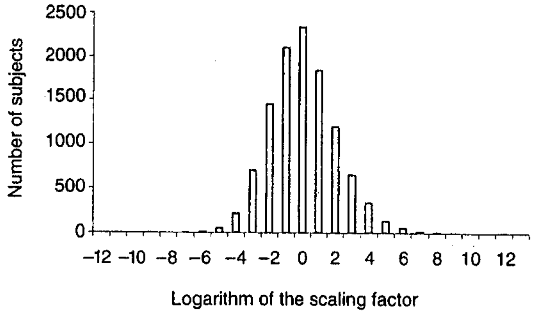

Figure 5. Distribution of the logarithm of the thyroid dose ratio (ecological/instrumental) for all Belarusian subjects in the cohort.

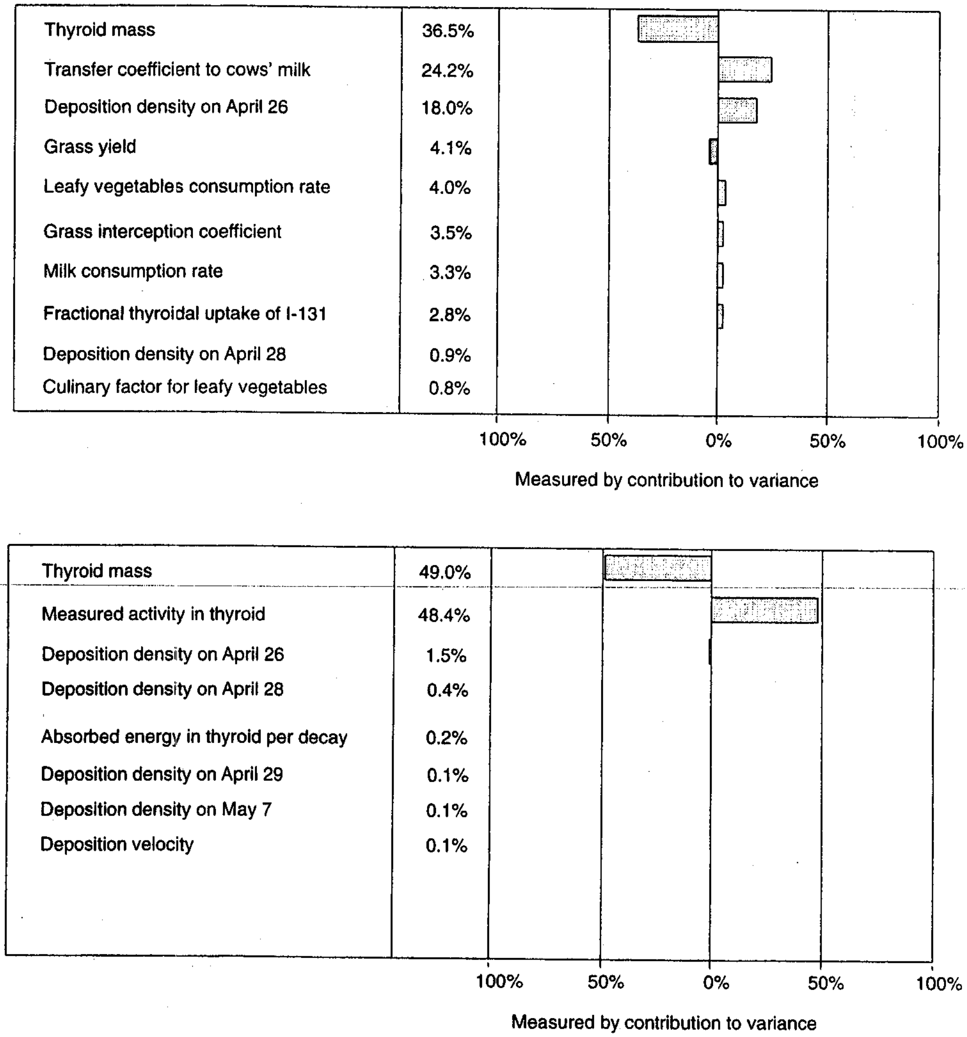

Figure 4. Sensitivity analysis for a Belarusian subject: top, ecological method; bottom, instrumental method.

sensitivity analysis of the contributions of the various parameters to the uncertainty for a typical subject are shown in Figure 4. The parameters that account for most of the uncertainty are the thyroid mass, the transfer coefficient from pasture intake to cows' milk, and the deposition density on the ground; other less important parameters are the pasture grass yield, the interception coefficient of ^{131}I by pasture grass, the consumption rates of milk and leafy vegetables and the thyroidal uptake of ^{131}I.

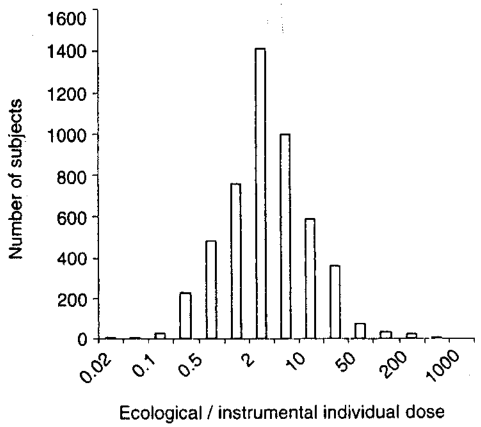

Figure 6. Distribution of the ratios of the individual ecological and instrumental doses for the subjects in the Ukrainian cohort.

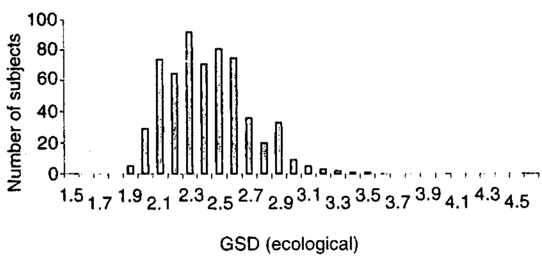

Figure 7. Distribution of the geometric standard deviation (GSD) of the thyroid dose for the Belarusian cohort subjects (ecological model).

CONCLUSIONS

For the first time, a large number of individual thyroid doses, and their uncertainties, resulting from the large releases of ^{131}I that occurred during the Chernobyl accident have been estimated in the framework of an epidemiological study of thyroid diseases conducted by the NCI in collaboration with the ministries of health of Belarus and Ukraine. As far as possible, the same methodology of thyroid dose reconstruction was used for the subjects originating from the two countries considered.

The uncertainties in the thyroid dose estimates resulting from ^{131}I intakes are found to be, to a first approximation, log–normally distributed. For dose estimates based on thyroid activity measurements, the geometric standard deviations associated with these distributions vary from one individual to another and range from 1.6 to 5.0. The medians of the geometric standard deviations are 1.7 for the Ukrainian subjects and 2.1 for the Belarusian subjects. The parameters that account for most of the uncertainty are the thyroid mass and those related to the determination of the content of ^{131}I in the thyroid at the time of the direct thyroid measurement.

Although these estimates of thyroid dose and of their uncertainties will be used at this stage of the epidemiological study, all aspects of the dose estimation process are being re-evaluated, so that more accurate and precise thyroid dose estimates resulting from ^{131}I intakes could be derived in a few years. In addition, the revised thyroid dose estimates will include the contributions resulting from the intake of short-lived radioiodines (^{133}I and ^{135}I) and radiotelluriums (^{131m}Te and ^{132}Te), from the intake of the long-lived radiocaesiums (^{134}Cs and ^{137}Cs), and from external irradiation arising from the deposition of radionuclides on the ground and other materials;

ACKNOWLEDGEMENTS

This work was supported by funds from the US National Cancer Institute, the US Department of Energy, the US Environmental Protection Agency and the ministries of health of Ukraine and of Belarus. The authors also want to thank their numerous American, Belarusian, Russian and Ukrainian colleagues who contributed to the preparation of this paper.

REFERENCES

1. UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation). *Sources and Effects of Atomic Radiation). Sources and Effects of Ionizing Radiation.* United Nations sales publication E.00.IX.3 (New York: United Nations) (2000).
2. Kazakov, V. S., Demidchik, E. P. and Astakhova, L. N. *Thyroid cancer after Chernobyl.* Nature **359**, 21 (1992).
3. Likhtarev, I., Sobolev, B. G., Kairo, I. A., Tronko, N. D., Bogdanova, T. I., Oleinic, V. A., Epshtein, E. V. and Beral, V. *Thyroid cancer in Ukraine.* Nature **375**, 365 (1995).
4. Gavrilin, Y. I., Khrouch, V. T., Shinkarev, S. M., Krysenko, N. A., Skryabin, A. M., Bouville, A. and Anspaugh, L. R. *Chernobyl accident: reconstruction of thyroid dose for inhabitants of the Republic of Belarus.* Health Phys. **76**, 105–119 (1999).

5. Likhtarev, I. A., Shandala, N. K., Gulko, G. M., Kairo, I. A. and Chepurny, N. I. *Ukrainian thyroid doses after the Chernobyl accident.* Health Phys. **64**, 594–599 (1993).

6. Astakhova, L. N. and 17 others. *Chernobyl-related thyroid cancer in children of Belarus: a case-control study.* Radiat. Res. **150**, 349–356 (1998).

7. Gavrilin, Y., Khrouch, V., Shinkarev, S., Drozdovitch, V., Minenko, V., Shemiakina, E, Ulanovsky, A., Bouville, A., Anspaugh, L., Voillequé, P. and Luckyanov, N. *Individual thyroid dose estimation for a case-control study of Chernobyl-related thyroid cancer among children of Belarus. Part I: short-lived radioiodines (^{132}I, ^{133}I, ^{135}I), and short-lived radiotelluriums (^{131m}Te and ^{132}Te).* Health Phys. (submitted).

8. Jacob, P., Kenigsberg, Y., Zvonova, I., Goulko, G., Buglova, E., Heidenreich, W. F., Golovneva, A., Bratilova, A. A., Drozdovitch, V. and Paretzke, H. G. *Childhood exposure due to the Chernobyl accident and thyroid cancer risk in contaminated areas of Belarus and Russia.* Br. J. Cancer **80**, 1461–1469 (1999).

9. Minenko, V., Shemyakhina, E., Tretyakevich, S., Ulanovsky, A., Shinkarev, S., Gavrilin, Y., Khrouch, V., Bouville, A., Voillequé, P. and Luckyanov, N. *Chernobyl accident: revision of individual thyroid dose estimates for the children included in the cohort of the Belarusian-American study.* In: Proceedings of the 10th International Congress of the International Radiation Protection Association (IRPA-10). Hiroshima, Japan, 14–19 May 2000. Paper T-12-2 (CD-ROM) (2000).

10. Wachholz, B. W. *United States cooperation with Belarus and Ukraine in the development and implementation of scientific protocols of thyroid cancer and other thyroid disease following the Chernobyl accident.* In: Nagasaki Symposium on Chernobyl: Update and Future, pp. 145–148 (Amsterdam: Elsevier Science) (1994).

11. Voillequé, P., International Committee for Research on Health Effects of Radiation, private communication (2002).

12. Cardis, E. International Agency for Research on Cancer, private communication (2002).

13. Ulanovsky, A., Minenko, V. and Korneev, S. *Influence of measurement geometry on the estimate of ^{131}I activity in the thyroid: Monte Carlo simulation of a detector and a phantom.* Health Phys. **72**(1), 34–41 (1997).

14. Likhtarev, I. A., Gulko, G. M., Sobolev, B. G., Kairo, I. A., Prohl, G., Roth, P. and Heinrichs, K. *Evaluation of the ^{131}I thyroid-monitoring measurements performed in Ukraine during May and June of 1986.* Health Phys. **69**(1), 6–15 (1997).